Remote Sensing of Environment 114 (2010) 563–575

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

MODIS snow albedo bias at high solar zenith angles relative to theory and to *in situ* observations in Greenland

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ARTICLE INFO

Article history:
Received 27 May 2009
Received in revised form 21 October 2009
Accepted 24 October 2009

Keywords:
MODIS
Snow albedo
Sun zenith angle
Greenland

ABSTRACT

In situ measurements of snow albedo at five stations along a north–south transect in the dry-snow facies of the interior of Greenland follow the theoretically expected dependence of snow albedo with solar zenith angle (SZA). Greenland Climate Network (GC-Net) measurements from 1997 through 2007 exhibit the trend of modest surface brightening with increasing SZA on both diurnal and seasonal timescales. SZA explains up to 50% of seasonal albedo variability. The two other environmental factors considered, temperature and cloudiness, play much less significant roles in seasonal albedo variability at the five stations studied. Compared to the 10-year record of these GC-Net measurements, the five-year record of MODIS satellite-retrieved snow albedo shows a systematic negative bias for SZA larger than about 55°. Larger bias of MODIS snow albedo exists at more northerly stations. MODIS albedos successfully capture the snow albedo dependence on SZA and have a relatively good agreement with GC-Net measurements for SZA < 55°. The discrepancy of MODIS albedo with *in situ* albedo and with theory is determined mainly by two related factors, SZA and retrieval quality. While the spatiotemporal structure, especially zonal features, of the MODIS-retrieved albedo may be correct for large SZA, the accuracy deteriorates for SZA > 55° and often becomes physically unrealistic for SZA > 65°. This unphysical behavior biases parameterizations of surface albedo and restricts the range of usefulness of the MODIS albedo products. Seasonal-to-interannual trends in surface brightness in Greenland, and in polar (i.e., large SZA) regions in general, and model simulations of these trends, should be evaluated in light of these limitations.

1. Introduction

Albedo is the fraction of incident solar energy reflected by the surface over the entire solar spectrum (Dickinson, 1983). The land surface albedo is one of the key parameters and a driver in climate and weather models since it regulates the shortwave radiation absorbed by the Earth surface (Lucht, 1998; Wang et al., 2005). Snow or ice covers about 40% of northern hemisphere land in winter and causes the greatest seasonal surface albedo variability (Qu & Hall, 2005). Snow and ice cover are important components of the Earth's energy balance because of their high reflectance in the visible bands and great seasonal variation. Fresh snow reflects more than 80% of incident solar energy. Snow albedo decreases as grain size increases (due to aging and/or warming) and due to accumulating impurities. The snow-albedo feedback amplifies the sensitivity of snow and ice to small changes in albedo (Stroeve et al., 2005; Flanner & Zender, 2005; Flanner et al., 2007). Accurate determination of snow albedo is therefore critical for understanding and predicting cryospheric climate sensitivity.

Snow bi-directional reflectance varies strongly with solar zenith angle (SZA) and viewing geometry (Wiscombe & Warren, 1980; Jin et al., 2003a,b; Salomon et al., 2006), and snow directional–hemispherical reflectance (DHR) has a far greater magnitude of increase with SZA in infrared wavelengths (1.03 µm) than in visible (0.55 µm) wavelengths (Schaepman-Strub et al., 2006). The hemispherically integrated flux reflectance, or spectral albedo, integrates this angular variation at a given wavelength. The scalar of greatest interest to climate studies is the spectrally integrated broadband solar albedo which describes the net flux reflectance of the land surface. Near-global maps of surface albedo retrieved from satellite measurements are available from multiple instruments that include the Advanced Very High Resolution Radiometer (AVHRR), the Earth Radiation Budget Experiment (ERBE), Polarization and Directionality of the Earth's Reflectances (POLDER), Clouds and the Earth's Radiant Energy System (CERES), and the MODerate resolution Imaging Spectroradiometer (MODIS) (Schaaf et al., 2008a). Accurate MODIS snow albedos are of particular value to climate research because the two platforms (Terra and Aqua) sample the cryosphere, which is rapidly changing, at high temporal and spatial resolutions relative to the other platforms.

Satellite-estimated albedo products rely on sophisticated radiative transfer methods and bidirectional modeling to predict and compute

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0034-4257/$ – see front matter © 2009 Elsevier Inc. All rights reserved.
doi:10.1016/j.rse.2009.10.014

the surface quantities at different solar illumination and viewing zenith angles based on limited satellite retrievals (Schaaf, et al., 2008a). These radiative transfer methods and models used in MODIS, such as the Ambrals Ross-Thick Li-Sparse Reciprocal (RTLSR), Bidirectional Reflectance Distribution Function (BRDF), may produce unreliable albedos when SZA is large (>70°) (Lucht, 1998; Schaaf et al., 2002; Wang et al., 2005; Liu et al., 2009). The long-term ground-based albedo observations from the Greenland Climate Network (GC-Net) over the near homogeneous snow surface provide good opportunities to validate and improve the remotely sensed satellite albedos (Stroeve et al., 2005).

Greenland's snow and ice play pivotal roles in the global climate because of their year-long high reflectivity (or albedo), large area and substantial volume of fresh water stored (Steffen & Box, 2001). The high SZA poses serious challenges not only to *in situ* solar radiation measurements (Augustine et al., 2000), but also to the consistency and accuracy of the MODIS radiative transfer models applied to polar regions (Lucht, 1998; Liu et al., 2009). Assuming that snow surface structure and conditions (related to snow grain size, age, contamination, etc.) do not change, theory shows that snow surface albedo increases with SZA (Fig. 1) because the increased path over which obliquely-incident photons interact with snow grains allows more multiple scattering and less penetration or absorption by the snow surface. This results in a larger fraction of solar radiation reflected by snow (Warren & Wiscombe, 1980; Wang et al., 2005; Lucht, 1998). Several field studies show albedo increases with SZA not only over snow, but also over desert, vegetated and ocean surfaces as well (Warren & Wiscombe, 1980; Jin et al., 2003b; Painter & Dozier, 2004; Wang et al., 2005; Liu et al., 2009).

The existence of a MODIS snow albedo bias at high SZA is also noted by Hall et al. (2009a). We will show that this bias leads to substantial underestimates of climatological albedo. The standard MODIS BRDF/Albedo algorithm estimates the albedo at local noon (Lucht, 1998; Schaaf et al., 2002; Jin et al., 2003a). Jin et al. (2003b) show (1) that *in situ* albedo measurements do follow, and that MODIS standard albedo retrievals do *not* follow, the expected SZA-albedo relation at large zenith angles. The overall accuracy of MODIS albedo is within 0.05 as compared to the ground observations at the Oklahoma

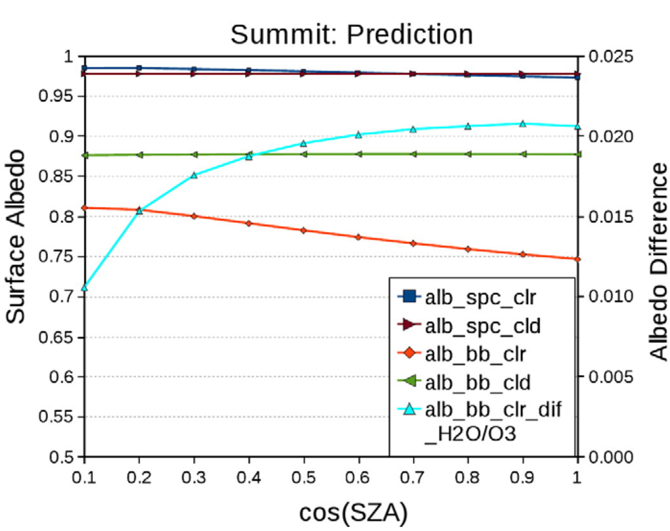

Fig. 1. Predicted dry snow surface spectral (spc = 0.5 µm) and broadband (bb = 0.28–2.80 µm) albedo versus solar zenith angle (SZA) under clear (clr) sky and overcast cloud (cld) sky at the Summit station (72.5794 N, 38.5042 W) of Greenland, and the broadband albedo difference for clear sky between atmospheric H_2O/O_3 absorption and no atmospheric H_2O/O_3 absorption. Snow density is 250.0 kg m^{-3}, grain radius is 200 µm, and grain size distribution is 1.6. Detailed model and theory description are documented by Zender (1999) and Flanner and Zender (2006).

CART site and has an increasing negative bias when SZA > 70° (Liu et al., 2009). High quality MODIS snow albedo retrievals can be obtained over the homogeneous snow surfaces on Greenland, usually for SZA < 55–60°, and larger errors exist at high SZA (Stroeve et al., 2005). These large errors may bias parameterizations of surface albedo and restrict the range of usefulness of the MODIS product. Moreover, these errors also undermine measurement-based evaluation of climate model albedo estimates over Greenland, Antarctica, and other high latitude snow-covered regions (Zhou et al., 2003; Oleson et al., 2003).

This study therefore aims to characterize, understand, and address the influence of SZA on both *in situ* and remotely sensed snow albedo and their discrepancy. Our strategy adopts the *in situ* GC-Net solar radiation observations at the perennial snow-covered stations on Greenland to evaluate the MODIS albedo product. First we analyze diurnal and seasonal cycles of albedo and solar radiation. We then identify the SZA dependence of, and air temperature impacts on snow albedo using the *in situ* measurements. Finally we compare the MODIS albedo with *in situ* measurements and quantify the bias of MODIS snow albedo at high SZA from several aspects.

2. MODIS and AWS data

2.1. MODIS albedo products

MODIS is used in two distinct sets of 16-day BRDF/albedo products. One is the Terra-only 1 km MOD43B in an Integrated Sinusoidal Grid (ISG) projection with standard tiles representing 1200 × 1200 gridpoints and 0.05° MOD43C in the Climate Modeling Grid (CMG) (Schaaf et al., 2002). The other is the Terra and Aqua MODIS combined products (MCD), which includes 500 m MCD43A and 1 km MCD43B in ISG projection, and the global 0.05° MCD43C in the CMG projection. Both Terra and Aqua data are used to generate this product. The combination provides the highest probability for quality input data, and increases full retrievals across the globe by 50% (Salomon et al., 2006). The 500 m product is first produced at the latest version 5 in the combined product (Schaaf et al., 2008b). Version-5 MODIS/Terra +Aqua BRDF/Albedo products are validated stage 1 and its accuracy has been estimated using a small number of independent measurements obtained from selected locations and time periods and ground-truth/field program efforts. In addition, there is another daily albedo product developed by Klein and Stroeve (2002) and Stroeve et al. (2006), discussed in Hall et al. (2009a), and used over the Greenland Ice Sheet by Hall et al. (2009b).

Each of the five products (two Terra MODIS-only and three Terra and Aqua MODIS combined) consists of four components. The first two components are seven spectral bands (MODIS bands 1–7, e.g., MCD43C1) and three broadbands' (0.3–0.7, 0.7–5.0, and 0.3–5.0 µm, e.g., MCD43C2) BRDF model parameters from which users can reconstruct the entire BRDF and compute the directional reflectance at any view or desired sun zenith angle. Thus, the directional hemispheric reflectance (black-sky albedo, BSA) at any angle and further the bihemispheric reflectance (white-sky albedo, WSA) can be generated. For consistency, we use the reflectance terminology employed in much, but not all, of the relevant MODIS literature (Schaaf et al., 2002; Stroeve et al., 2005), such as MODIS BRDF/albedo product, white-sky albedo and black-sky albedo. Here BRDF, white-sky albedo and black-sky albedo respectively represent the bidirectional reflectance distribution function (BRDF; Case 1), directional hemispheric reflectance (DHR; Case 3) and bihemispheric reflectance (BHR; Case 9) as documented in Schaepman-Strub et al. (2006). The third component (e.g., MCD43C3) is the standard suite of albedo values for black-sky and white-sky of the seven MODIS spectral bands and the three broadbands. The black-sky albedos are reported for the local noon SZA at each gridpoint. The final component (e.g., MCD43C4) is the nadir viewing BRDF-Adjusted Reflectance (NBAR)